Approximation -free prescribed performance control for Nonlinear morphing missile System

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Abstract— **This paper deals with the design of a robust prescribed performance control (PPC) approach for nonlinear morphing missile systems with unknown dynamics and uncertainties. prescribed performance function (PPF) is integrated into the control design, such that capable of guaranteeing, for any a priori known initial state condition, bounded signals in the closed loop, as well as prescribed performance for the output tracking error, We propose a systematic control design procedure, where the proportional-like controls are obtained by using the transformed tracking errors with PPF. Finally, extensive simulations are conducted based on linear and nonlinear morphing missile to validate the convergence performance and the robustness of the investigated control method**

Index Terms— **morphing missile system, nonlinear system prescribed performance control (PPC), prescribed performance function (PPF), robust control**

I. INTRODUCTION

The concept of morphing is to guarantee the ability of a flying structure to obtain better flight performance, to accommodate multiple flight regimes according to the different flight missions, and to achieve certain maneuvers or specifications by means of in-flight shape changing. In practical applications, these shape variations may be continuous, smooth and seamless in corresponding to the time-varying camber, wing twist and self-adapting wings which are essential for improving the overall aircraft performance during the past several years, adaptive control of systems possessing complex and unknown nonlinear dynamics has attracted considerable research effort. Significant progress has been achieved through adaptive feedback linearization[1], adaptive back stepping [2], control Lyapunov functions [3] and adaptive neural network/fuzzy logic control [4].The aforementioned results were obtained for systems in affine form, that is, for plants linear in the control input variables. However, there exist practical systems such as chemical processes and flight control systems, which can not be expressed in an affine form The difficulty associated with the control design of such systems arises from the fact that an explicit inverting control design is, in general, impossible, even though the inverse exists. Initially, no affine systems in low triangular canonical form

(i.e., system nonlinearities satisfy a matching condition) were considered. Subsequently, as the problem became more apparent, the significantly more complex as well as general class of pure feedback non affine systems (i.e., all system states and control inputs appear implicitly in the system nonlinearities) was tackled. Works incorporating the Mean Value Theorem [5]-[13], the Taylor series expansion [14] and the contraction mapping method [15]-[16] have been proposed to decompose the original non affine system into an affine in the control part and a no affine part representing generalized modeling errors. Subsequently, standard robust adaptive control tools were employed. However, approximating this "ideal controller "a difficult task, leading also to complex neural network and fuzzy system structures. In [17]- [18], instead of seeking a direct solution to the inverse problem, an analytically invertible model was introduced and a neural network was designed to compensate for the inversion error. However, another critical issue in the control design for morphing missile systems is the transient tracking response. This is particularly important for their safe operation, because the missile systems with very aggressive transient control performance (e.g. overshoot, oscillation and convergence rate) may be broken before they reach the steady-state.

The objective of this paper is to further study the PPC design and PID control for nonlinear morphing missile systems subject to uncertainties and disturbances, and to present a robust control with guaranteed steady-state and transient performance without using any function approximator. The paper is organized as follows. Section **II** presents the mathematic model of Morphing UAV systems,. In Section **III**, a robust approximation-free control design is provided, and the closed-loop system stability is also rigorously proved. In Section **IV**, simulations are given to demonstrate the efficacy and the improved performance of the suggested algorithm. Finally, some conclusions are presented in Section **V**.

II. PROBLEM STATEMENT AND PRELIMINARIES

A. Dynamics of Morphing missile System

This paper will study the control design for morphing UAV or missile systems. A typical control and guidance process of nonlinear morphing missile systems can be given in Fig. 1

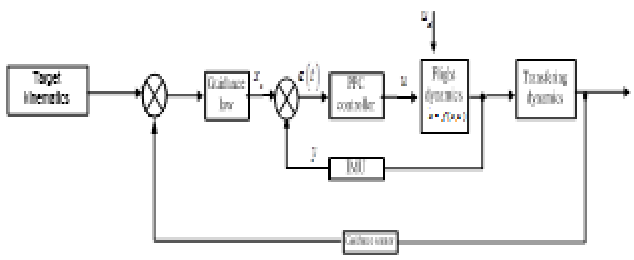

Fig.1 overall control structure of morphing missile system

In this paper, we will present the dynamics and the associated control design for the attitude loop, which can

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make the flight dynamics to track a given reference x_c. The system states, e.g. the pitch speed q and the acceleration of the mass center n_y, are all measured by using the inertial measurement units (IMU) with three-axis gyros and three-axis accelerometer. For the purpose of control design, we consider the following nonlinear morphing missile systems in the pitch plane.

$$\begin{cases} \dot{n}_y = f_1(n_y, q) \\ \dot{q} = f_2(n_y, q, \delta_q, d) \end{cases} \quad \textbf{(1)}$$

Where the control input δ_q denotes the deflection of the control surface. The nonlinear force or moment vector $f_i(n_y, q), i = 1, 2$ are continuous functions of their

coordinates, and u_d represents the model uncertainties and external disturbances imposed on the morphing UAV. It is noted that the system representation (1) is generic as it can cover versatile systems, e.g. linear systems, nonlinear systems in canonical form, strict-feedback form or pure feedback form (as shown in simulation section).

Assumption 1 the nonlinear function $f_i(n_y, q), i = 1, 2$ are continuous and there exist

unknown positive constant $g_{1,} g_2 > o$ such that

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unknown positive constant $g_{1,} g_2 > o$ such that :

$$\frac{\partial f_1(n_y, q)}{\partial q} \geq g_{1,} \; \frac{\partial f_2(n_y, q, \delta_q, d)}{\partial q} \geq g_2, \forall (n_y, q, \delta_q, d) \in R^3$$

Moreover, the

Signs of $\frac{\partial f_1(n_y, q)}{\partial q}$ and $\frac{\partial f_2(n_y, q, \delta_q, d)}{\partial q}$ are strictly positive or negative. Without loss of generality, we assume they are all positive in this paper

Remark 1: Assumption 1 indicates that the control in put gains must be non zero for all t>0. This a well known controllable condition in the control system designs .this condition can be fulfilled in most practical systems(e.g. morphing system (1)and this not stringent .moreover ,in contrary to a variable control methods for system (1),we we do need any precise knowledge of the system nonlinearities or even of their upper bounds. The objective of the control design is to find an appropriate control input δ_q such that (1) the system output n_y tracks a given command x_c to achieve the desired guidance;2)transient and steady-state response of the tracking error $e_1(t) - n_y(t) - x_c(t)$ can be ensured within a given prescribed set.

B. Prescribed Performance Function

As stated in above, the control design can characterize both, the transient and steady-state error response, e.g. the error convergence rate, maximum overshoot and the allowable steady-state error. Thus, we will further explore the idea of PPC. The basic principle is to introduce a PPF and the associated error transform. However, the nonlinear system dynamics should be fully known or estimated in terms of function approximators. This issue will be tackled by introducing a new approximation-free control scheme with low complexity in this paper. We first introduce the following positive decreasing smooth function $\rho(t): R^+ \to R^+$ as PPF

$$\rho(t) = (\rho_0 - \rho_\infty)e^{-lt} + \rho_\infty \quad \textbf{(2)}$$

Where ρ_0, ρ_∞ and l are all positive constants selected by the designers which determine the initial error bound, ultimate error bound and the convergence speed,

Respectively apparently, the PPF (2) fulfills the following conditions

(i) $\rho(t)$ is positive and decreasing;

(i) $\lim_{t\to\infty} \rho(t) = \rho_\infty > 0, \lim_{t\to 0} \rho(t) = \rho_0$

Thus, the control design objective

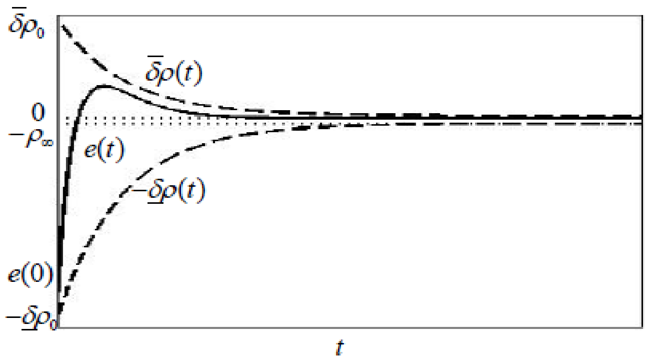

Figure **2. Prescribed tracking error bound**

With $\rho(t) = (\rho_0 - \rho_\infty)e^{-lt} + \rho_\infty$

The constant ρ_∞ represents the maximum allowable size of the tracking error e_1 in the steady-state, the decreasing rate l introduces a lower bound on the required convergence speed of e_1, and the maximum overshoot is determined by min $\{\bar{\delta}\rho_0, \underline{\delta}\rho_0\}$, which may even be set as zero by setting $\bar{\delta}$, $\underline{\delta} = 0$. Thus, the performance function ρ (t) and the constants ρ_0, ρ_∞, l, and $\bar{\delta}$, $\underline{\delta}$ can be appropriately selected to specify both the transient and steady-state performance of e_1 .Moreover, to solve the control problem with prescribed performance (3), an error transform will be introduced by transforming the condition (3) into an equivalent "unconstrained". For this purpose, we define a smooth, strictly increasing function of the transformed error $\lambda_i(t) \in R$ such that:

(i) $\underline{\delta} < s(\lambda_i) < \bar{\delta}, \forall \lambda_i \in L_\infty$

(ii) $\lim_{\lambda_i\to+\infty} s(\lambda_i) = \bar{\delta} and \lim_{\lambda_i\to-\infty} s(\lambda_i) = -\underline{\delta}$

In the subsequent control design, we will use the following function:

1) can be achieved by retaining $e(t)$ within a predefined set by using $\rho(t)$ which can be given as $:-\underline{\delta}\rho(t)<e_1(t)<\overline{\delta}\rho(t),\forall t>0$ **(3)**

Where $\overline{\delta},\underline{\delta}$ >0 are all positive constants. In figure 2 with an exponentially decaying performance function

$$s(\lambda_i)=\frac{\overline{\delta}e^{\lambda_i}-\underline{\delta}e^{\lambda_i}}{e^{\lambda_i}+e^{-\lambda_i}} \quad \textbf{(4)}$$

Since $s(\lambda_i)$ is strictly monotonic increasing, the inverse function of $s(\lambda_i)$ exists and can be given as:

$$\varepsilon_i=s^{-1}[\lambda_i]=\tfrac{1}{2}\ln\left(\frac{\underline{\delta}+\lambda_i}{\overline{\delta}-\lambda_i}\right) \quad \textbf{(5)}$$

III. Prescribed Performance Control Design

In this section, we will design a control to guarantee both the transient and steady-state performance, where the widely used functional approximation is avoided

A. Controller Design

Since the studied system (1) is not in the standard canonical form, a recursive design procedure will be conducted to achieve the control objective. This can be processed as:

Step 1: Define the output tracking error:

$$e_1(t)=n_y(t)-x_c(t) \quad \textbf{(6)}$$

Then we design the transformed error as

$$\varepsilon_1(t)=s^{-1}(\lambda_1(t)) \quad \textbf{(7)}$$

Where $\lambda_1(t)={}^{e_1(t)}\!/\!_{\rho_1(t)}$ is the normalized output error by using a similar PPF defined in (3) as

$$\rho_1(t)=(\rho_{10}-\rho_{1\infty})e^{-l_1t}+\rho_{1\infty} \quad \textbf{(8)}$$

Where the constant ρ_{10} , $\rho_{1\infty}$ and l_1 are all positive, and ρ_{10} , can be set to fulfill $|e(0)|<\rho_{10}$ In this case,

One may verify from (5) and (7) such that

$$\varepsilon_1=s^{-1}(\lambda_1)=\tfrac{1}{2}\ln\left(\frac{\underline{\delta}+\lambda_1}{\overline{\delta}-\lambda_1}\right) \quad \textbf{(9)}$$

We can introduce an intermediate control

$$q_d=-k_1\varepsilon_1=-\tfrac{k_1}{2}\ln\left(\frac{\underline{\delta}+\lambda_1}{\overline{\delta}-\lambda_1}\right) \quad \textbf{(10)}$$

Where k_1 > 0 is the control gain, which can be set as appositive constant

Step 2: Define the intermediate control error as:

$$e_2(t)=q(t)-q_d(t) \quad \textbf{(11)}$$

Where is the desired intermediate control given in (10) Similar to Step 1, we design the normalized error as $\lambda_2(t)={}^{e_2(t)}\!/\!_{\rho_2(t)}$ with $\rho_2(t)$ being a PPF given by

$$\rho_2(t)=(\rho_{20}-\rho_{2\infty})e^{-l_2t}+\rho_{2\infty} \quad \textbf{(12)}$$

Where ρ_{20} , $\rho_{2\infty}$, and l_2 are all positive constant , and ρ_{20} ,is set to fulfill $|e_2(0)|<\rho_{20}$ Thus, the transformed error of $s(\lambda_2)$ is defined as $\varepsilon_2=s^{-1}(\lambda_2)=\tfrac{1}{2}\ln\left(\frac{\underline{\delta}+\lambda_2}{\overline{\delta}-\lambda_2}\right)$ where the error transform function $s(\lambda_2)$ is described in (5). Finally, a realistic control can be designed as

$$\delta_q=-k_2\varepsilon_2=-\tfrac{k_2}{2}\ln\left(\frac{\underline{\delta}+\lambda_2}{\overline{\delta}-\lambda_2}\right) \quad \textbf{(13)}$$

Where k_2 > 0 is a positive constant control gain.

It is shown that the above recursive design procedure follows a similar design principle to backstepping approaches .so that it can be easily extended to high order systems .moreover ,the suggested control formulations (10)and (13) are proportional-like controls with the normalized errors $\lambda_i(t)$ and the error transform function $\varepsilon_i=s^{-1}(\lambda_i)$. Another salient feature of the proposed control (13) with (10) is that no precise knowledge of system nonlinearities or their upper bounds are required. Consequently, the widely used function approximates are not necessary In this sense, the overall control implementation has significantly reduced complexity.

Remark 2: In this paper, the control objective is to guarantee the predefined transient and steady-state performance (3) for the output tracking error $e_1(t)$ We also introduce an intermediate control error $e_2(t)$ in (10) with PPF, which can help to improve the overall control response. Moreover, the initial conditions $|e(0)|<\rho_{10}$ and $|e_2(0)|<\rho_{20}$ are required in the following stability analysis, which can be trivially fulfilled by selecting appropriate PPF parameters ρ_{10} and ρ_{20} .

B. Stability analysis

This subsection will study the closed-loop system stability and the convergence of the presented control schemes. Before we present the main results of this paper, the following lemma is introduced :

Lemma 1: If the transformed errors $\varepsilon_i=s^{-1}(\lambda_i)$ are bounded, $|\varepsilon_i|\le\varepsilon_{Mi}$ hold for positive constants $\varepsilon_{Mi}>0$, then $-\underline{\delta}\rho_i(t)<e_i(t)<\overline{\delta}\rho_i(t),\forall t>0$

Proof: From the definition and property of the error transform function (5), we take the inverse logarithmic function and know that

$$e^{2\varepsilon_i}=\frac{\underline{\delta}+\lambda_i}{\overline{\delta}-\lambda_i} \quad \textbf{(14)}$$

This further implies

$$-\underline{\delta} < \frac{e^{-\varepsilon Mi}\,\overline{\delta}-\underline{\delta}}{e^{-\varepsilon Mi}+1} \le \lambda_i\left(t\right) \le \frac{e^{-\varepsilon Mi}\,\overline{\delta}-\underline{\delta}}{e^{-\varepsilon Mi}+1} < \overline{\delta}$$

Consequently, from the fact $\lambda_i\left(t\right)=e_i\left(t\right)/\rho_i\left(t\right)$ one may verify that $-\underline{\delta}\rho_i\left(t\right)<e_i\left(t\right)<\overline{\delta}\rho_i\left(t\right),\forall t>0$ holds. This completes the proof. Now, the main results of this paper can be summarized as follows

Theorem 1: For nonlinear system (1), we design an approximation-free control (13) with (10), if the initial condition fulfills $-\rho_i\left(0\right)<e_i\left(0\right)<\rho_i\left(0\right)$, then all signals in the closed-loop system are bounded, and the output tracking error $e_1\left(t\right)=n_y\left(t\right)-x_c\left(t\right)$ can be retained within a prescribed set defined in (3).

IV. SIMULATIONS

In this section extensive simulations are presented to validate the suggested control algorithms and to show the improvement of the control performance in comparison to standard PID control and feedback linearization control.

A. Linear Missile System

We first validate the performance of the proposed controller by using a linear morphing missile

system: $\dot{x}=Ax+Bu$

$$x=\begin{bmatrix}x_1\\x_2\end{bmatrix}=\begin{bmatrix}n_y\\q\end{bmatrix},A=\begin{pmatrix}-a_{34}n_y & \frac{v}{g}a_{34}\\ \frac{g}{v}\frac{a_{24}}{a_{34}} & a_{22}\end{pmatrix},B=\begin{bmatrix}0\\a_{25}\end{bmatrix} \quad \textbf{(15)}$$

Where the system parameters are defined as $a_{34}=1.37135s^{-1}$ $a_{24}=-45.5462s^{-2}$, $a_{22}=-0.1504s^{-1}$, $a_{25}=59.7238s^{-2}$, $V=204m/s$, $g=9.8m/s^2$ .clearly, the proposed (13)system (15) is a linear system, which can be taken as a specific form of the model (1). The initial conditions of the proposed controller are set $x=\left[0,0\right]^T$, and the PPF is, $\overline{\delta}=1$, $\underline{\delta}=1$,and the control gain is $k_i=1$ A unit step signal $x_c=1$ is adopted as the reference Figs. 3-5 give the control responses of the morphing missile system with the proposed PPC and a standard PID control $\delta_z=1.0e_1+0.1\int e_1dt+0.5\dot{e}_1$)From Fig. 3 and Fig. 4, it shows that the system states *y n* and *q* can accurately and quickly track the control command. Moreover, a fairly satisfactory tracking error response can be achieved with the proposed PPC as shown in Fig. 5, i.e. the tracking error converges to a small neighborhood of zero where the transient response can be retained within the predefined performance bound. However, the predefined transient bound cannot be guaranteed with the standard PID control, i.e. PID control produces large overshoot, which violates the given bound. Finally, it is shown in Fig. 6 that the control signal of the proposed control is bounded and smoother than that of PID control.

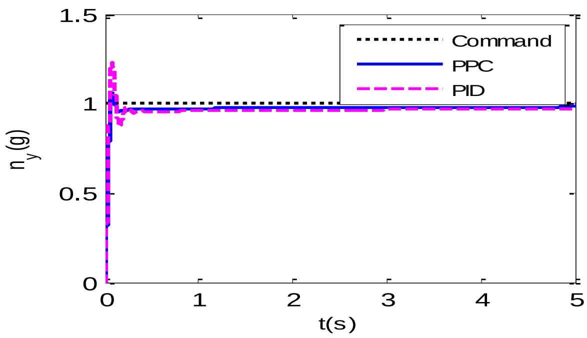

fig 3:response of control system output n_y

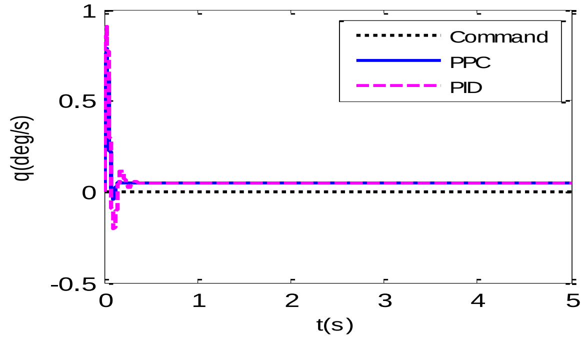

Figure:4 response of control state q

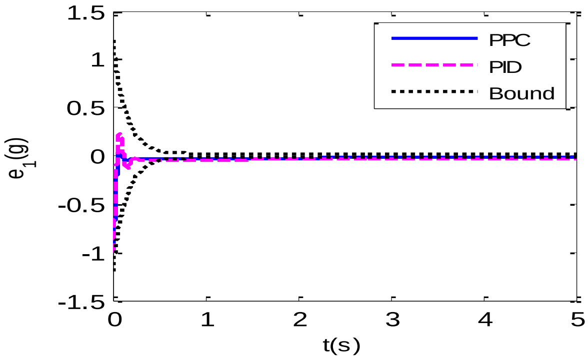

Fig:5 response of tracking error

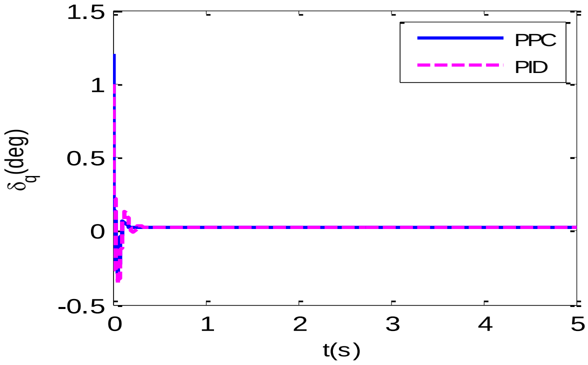

Figure: 6 control signals

B. Nonlinear Missile System

To show the ability of the suggested control scheme for nonlinear systems, we carry out simulations by using the following nonlinear dynamic missile system as:

$$\dot{x}=f\left(x\right)+g\left(x\right)u$$

$$x=\begin{bmatrix}x_1\\x_2\end{bmatrix}=\begin{bmatrix}n_y\\q\end{bmatrix},f(x)=\begin{bmatrix}-a_{34}n_y+\dfrac{V}{g}a_{34}q\\ \dfrac{g}{V}\dfrac{a_{24}}{a_{34}}n_y+a_{243}\left(\dfrac{g}{Va_{34}}n_y\right)^3+a_{22}q\end{bmatrix}$$

$$g(x)=\begin{bmatrix}0\\a_{25}\end{bmatrix},u=\delta_q \qquad \textbf{(16)}$$

Where $a_{243}=10^6s^{-6}$ It can be verified that the system (16) is indeed a strict-feedback nonlinear system. In this case, to fulfill the initial conditions and for fair comparison, the PPF parameters and other control parameters are all the same as those used in Case A, and the other parameters are the same as case 4.1. Moreover, we also test the feedback linearization (FL) control, which is given as $e_1=x_1-x_c$, $e_2=x_2-x_c$, $s=[A,1][e_1,e_2]$ and $u=\dfrac{1}{g(x)}\left[-ks-f(x)+\ddot{x}_c-[0,A][e_1,e_2]^T\right]$ with parameters $A=4$, $k=4$

Figs. 7-10 illustrate the control response of the morphing missile system (16) with PID control, feedback linearization control and the developed PPC scheme. From Fig. 7 and Fig. 8, it is shown that the profiles of n_y and q with the presented controller can accurately track the given commands, while both the transient and steady-state performance can be retained with the help of the used PPF (Fig. 9). On the other hand, the used PID controller leads to an aggressive transient response with fairly large overshoot although the convergence rate is faster than other two controllers. This may be because a large proportional gain is used in this case, which may result in oscillated control signal (Fig. 10). Moreover, the control response (i.e. output and control signal) of feedback linearization control is fairly smooth compared to the proposed control, although the transient convergence speed is slower than PPC as shown in Figs.9. However, it should be noted that the precise dynamics of system (16) should be fully known and used in this feedback linearization control scheme. Nevertheless, the proposed PPC in this paper does not use any information of the studied system. The simulation results illustrate the efficacy of the proposed robust approximation-free control, even with fully unknown nonlinear dynamics

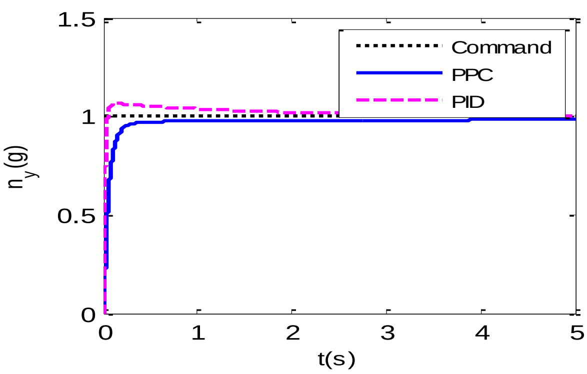

Figure 7: response of control system output n_y

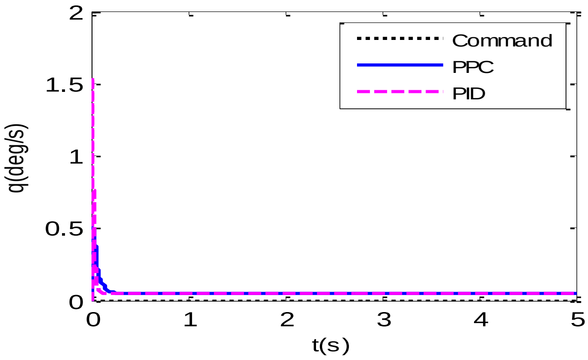

figure 8: response of control state q

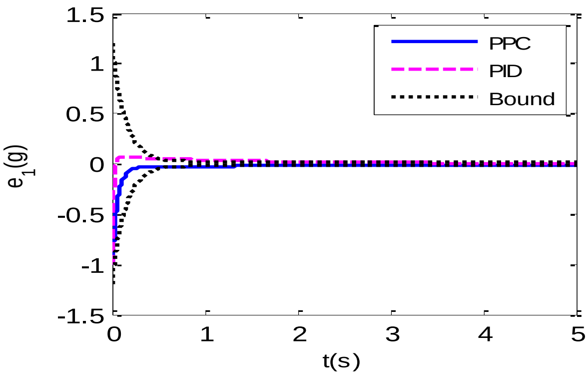

Figure**:** 9 response of tracking error

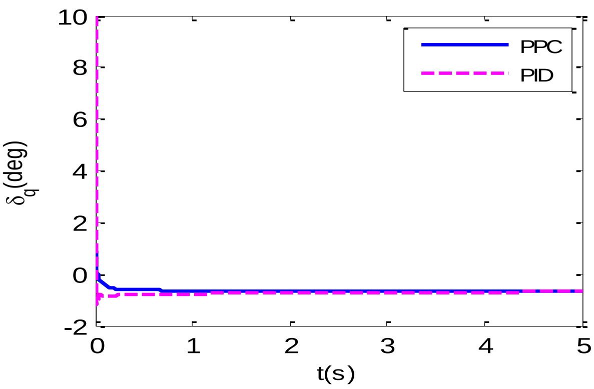

Figure**:**10 control signals

With External Disturbance

In order to test the robustness of the proposed control approach, we assume that the studied morphing UAV system (16) is perturbed with unknown disturbances, where d(t) is set as a uniform distribution signal with zero mean values. Figs. 11-14 show the comparative simulation results of the aforementioned two controllers (e.g.PID control, and PPC). Fig. 11 and Fig. 12 provide the response of the controlled system output and state with the two control methods. One may find that the proposed PPC can successfully compensate for the effects of both the nonlinearities and disturbance, and thus guarantee the predefined transient and steady-state convergence performance. However, PID control leads to significant tracking error; thus, we can conclude that the proposed PPC control can achieve better tracking performance although the required control signal (Fig. 14) has fair oscillations for necessarily compensating the disturbances.

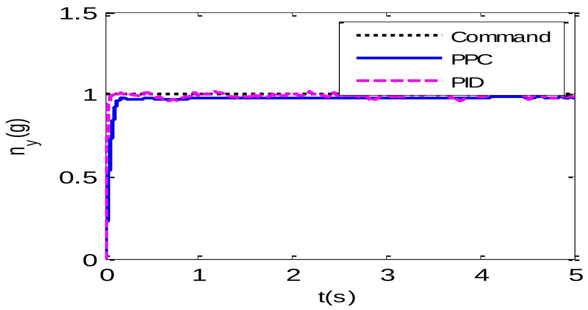

Figure11: response of control system output n_y

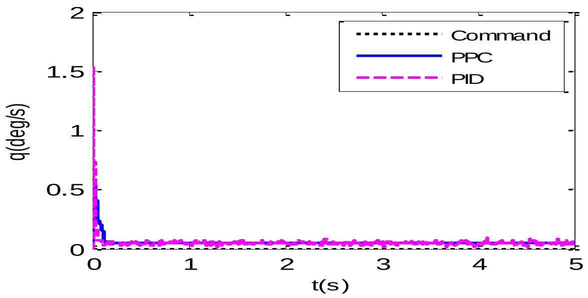

Figure:12,response of control state q

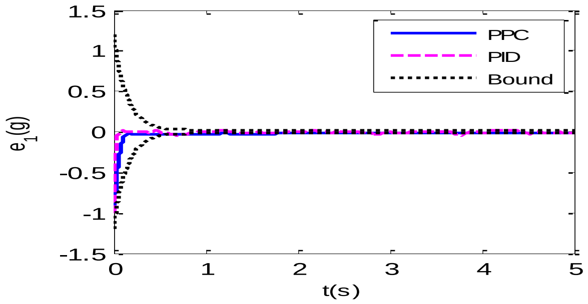

Figure: 13 response of tracking error

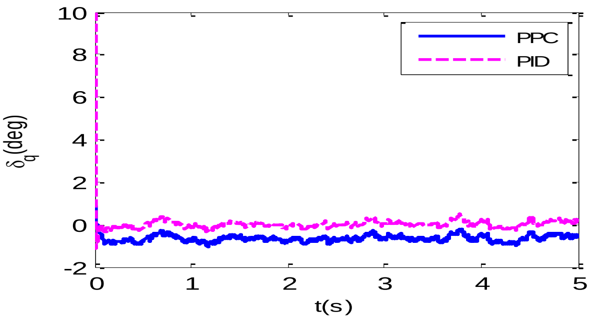

Figure: 14 control signals

All above simulation results illustrate the capability of the suggested approximation-free PPC to cope with the unknown nonlinear dynamics, and also the enhanced robustness against external disturbances. Moreover, the improvement of the transient and steady-state control performance is achieved owing to the used PPF and associate error transform strategies

V. Conclusions

This paper is concerned with the robust prescribed performance control design for nonlinear morphing missile system with unknown dynamics and disturbances. The proposed control can guarantee both the transient and steady-state control performance without using any function approximator. For this purpose, a modified prescribed performance function and the associated error transform are first suggested, and then they are incorporated into a systematic recursive design procedure for high order systems. Specifically, the transient and steady-state error convergence of the closed-loop system can be quantitatively studied and guaranteed by selecting appropriate design parameters in a *priori* manner. Comparative simulation results validate the theoretical studies and illustrate the improvement of the control performance.

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